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Designing reservoir sediment management alternatives with automated concentration constraints in a 1D sediment model

S. Gibson
US Army Corps of Engineers, Hydrologic Engineering Center, Davis, California, USA

P. Boyd
US Army Corps of Engineers, Omaha District, Omaha, Nebraska, USA

ABSTRACT: Sustainable reservoir management alternatives (e.g. flushing and routing) are often limited by downstream concentration constraints. Designing reservoir operations to pass sediment and maintain downstream concentration constraints can be difficult. A 1D sediment transport model (HEC-RAS) was developed for Spencer Dam and compared to measured results from a four week reservoir flush and the subsequent five months of reservoir deposition after the flush. Then the calibrated model was used to design two reservoir sediment re-operation alternatives to mitigate downstream effects. Sediment commands in the HEC-RAS Operational Rules feature automated gate operations for 1) concentration controlled flushing operations that limited downstream sediment releases to a defined limit and 2) sediment routing operations that limit downstream concentrations to the natural upstream concentrations flowing into the reservoir.

1 INTRODUCTION

Many dams built in Europe and North America during the early twentieth century construction boom are operating well beyond their original 'design life.' Since most still provide substantial benefits (e.g. the Missouri River cascade prevented billions of dollars of damages during the 2011 flood) agencies intend to operate many of them indefinitely. As these structures operate well beyond their original design, agencies and stake holders must consider sustainability strategies to extend their operational life and mitigate their environmental impacts.

The dam building experience in Europe and North America suggests that the most common dam ffailure modes are chronic and mostly involve sediment. Sediment deposition in the reservoir - upstream of the dam - is the most common and most intuitive chronic sediment problem associated with dams. The low energy lotic environment in the impoundment traps sediment. Decades of inflowing river load deposits, usually forming a prograding delta which fills the reservoir. However, downstream sediment impacts can also affect long term reservoir viability. Dams expose downstream reaches to long term sediment deficit. Downstream sediment deficit can threaten infrastructure or ecosystems (e.g. floodplain or mid-channel bar spawning) that depend on sediment continuity.

Outside of Europe and North America, public and private interests are actively building new dams, in some cases very quickly, with minimal long term analysis. These interests have the opportunity to plan long term reservoir sustainability into their structures and operations, recognizing that the reservoir 'design life' approach is obsolete .

Agencies considering sustainable sediment management commonly encounter two obstacles. The first obstacle is structural. Most twentieth century dams were not designed to manage sediment. They lack low level outlets or other infrastructure to flush deposits or route sediment laden flows. The second obstacle is regulatory. Resource agencies often limit reservoir flushing or routing, concerned that short term sediment releases will impact infrastructure or ecosystem function downstream. Resource agencies often enforce Total Maximum Daily Loads (TMDLs) set using post-dam, clear water conditions, effectively precluding reservoir sediment releases.

Two primary alternatives (Morris and Fan, 1998) can address downstream concerns about reservoir flushing impacts:

1. *Flush* reservoir sediment gradually, operating the structure to keep downstream concentrations below a specified concentration or TMDL.
2. *Route* the sediment laden portion of the hydrograph, timing operations to pass inflowing sediment during highest concentration flows, without increasing sediment concentrations above natural river transport.

Modeling these alternatives can be difficult since they include human operations, operational feedbacks tied to mid-simulation concentration triggers. Modelers cannot define responsive human actions as a priori boundary conditions for a sediment model. The U.S. Army Corps of Engineers (USACE) Hydrologic

Engineering Center (HEC) added sediment functionality to the Operational Rules in HEC-RAS 5.0 to model these alternatives. Adding sediment based operational rules to a mobile bed hydraulic model can automate concentration controlled flushing and routing simulations, allowing the sediment model to start or manage reservoir releases and drawdowns based on upstream or downstream concentrations, making simulations with operational feedbacks tractable.

HEC-RAS 5.0 has been applied to reservoir sediment management studies (Gibson and Boyd, 2014, Davis *et al*. 2014), but because actual sediment flushing events are rare in the United States, it has not been evaluated against field data. In an effort to bridge this gap, a team from the USACE and US Geological Survey (USGS) monitored and measured a reservoir flushing event at Spencer Dam on the Niobrara River (near Spencer, NE), and the reservoir deposition after the flush. HEC-RAS modeled both the sediment evacuated during the four week flush and the subsequent reservoir deposition five months after the flush. Then the concentration rules were applied to design flushing events based on downstream concentration limits and upstream concentration triggers.

2 SPENCER DAM FLUSH

Spencer Dam impounds a small reservoir on the Niobrara River, a sand bed river that flows into the Missouri River at Niobrara, NE in the central plains of the United States. The Niobrara catchment includes the Nebraska Sand Hills, which deliver substantial sediment loads (USACE, 2010). Spencer Dam and Reservoir were built in the late 1920's and filled with sediment within two decades of closure. Operators have flushed the reservoir twice a year nearly every year since.

In November 2014, the USACE and USGS team monitored a four week reservoir flush (Gibson and Boyd, 2016). Dam operators flushed the reservoir by opening four tainer gates (10.2 m wide, invert = 453.2 m) and a sluice gate (3 m wide, invert = 451.7 m). Because the reservoir pool was full of sediment, holding very little water, the reservoir drained to run of river conditions minutes after the sluice gate opened, pushing an initial head cut up through the reservoir in less than an hour (Figure 1).

The USGS measured downstream concentration during the flush and the USACE collected reservoir sediment gradations before and after the flush. The Omaha District of the USACE also collected repeated cross sections before the flush, immediately after the flush, and then again, almost five months after the end of the flush, to quantify the sediment volume evacuated during the flush and the reservoir deposition after it.

3 HEC-RAS SEDIMENT MODEL

HEC-RAS includes a one-dimensional hydraulic model, which computes water surface profiles and

Figure 1. Spencer Reservoir pool approximately 5 hours after opening the sluice gate.

inundation boundary maps based on steady flow back water computations or unsteady solutions to the Saint-Venant equation. HEC-RAS also includes a sediment transport model, which routes sediment through control volumes centred around each cross section. The sediment model updates the cross sections after each time step based on deposition or erosion in the control volume. HEC-RAS 5.0 couples sediment transport with unsteady flow. Coupling sediment transport with unsteady flow makes the "Operational Rules" feature, which changes gate operations mid-simulation based on model results (e.g. water surface elevation or flow at a specified cross section), available sediment transport studies (Gibson and Boyd, 2015). Sediment variables were added to the Operational Rules to automate model reservoir operations based on sediment concentration or bed change.

4 MODEL CALIBRATION

The sediment model was calibrated to bed volume change from the repeated cross section and measured downstream concentration for the four week flush. Then the model was calibrated to reservoir volume change during the five months of deposition in the reservoir after the flush. Both models used the same equations and parameters including the Yang transport equation (1972) and the Copeland mixing method (1993).

4.1 *Flush calibration*

The reservoir included clay lenses and cohesive forest beds, but relatively uniform sand filled most of the reservoir. Initial bed gradations in the model were set to an average bed gradation (65% MS and 25% VFS-FS). Seventeen pre-flush surface gradation samples, collected along a kilometer of the reservoir delta were averaged to compute this initial gradation. No other sediment parameters were adjusted to fine tune the flushing model.

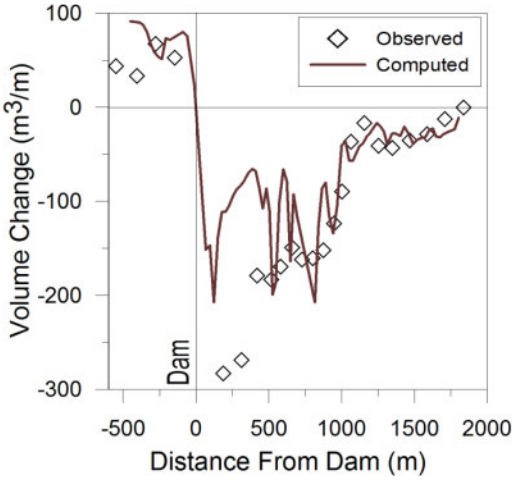

Figure 2. Bed change calibration for the reservoir flushing model. Both the observed and computed volume change are normalized by distance to account for different spacing.

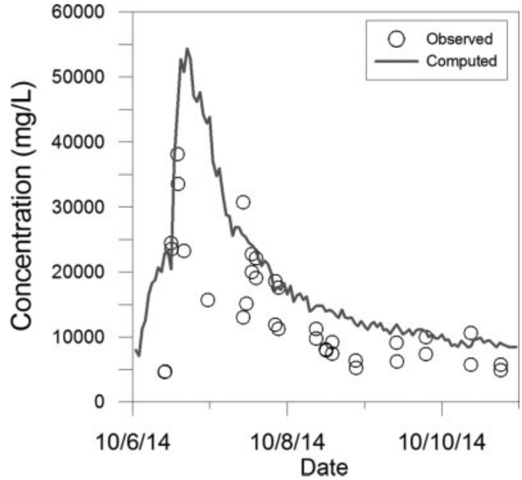

Figure 3. Concentration calibration for the reservoir flushing model. The concentration computed by HEC-RAS (based on total load) is plotted with suspended sediment concentrations collected 500m downstream of the flush.

Achieving stable solutions with a finite difference solution to the hyperbolic Saint-Venant equations can be challenging in a rapid drawdown situation with movable cross sections. HEC-RAS ran at a six second time step and interpolated additional cross sections between the measured cross sections, for a final cross section spacing of 20 to 30 meters. Braided channel forms often develop in the high load-to-gradient condition in reservoir deltas. Multiple channels that anastomose across the delta influence the flush, deepening and widening, until some of them are stranded and the dominant channel forms. If the interpolated model bathymetry does not preserve these channels, it will substantially under predict flushing volumes. HEC-RAS guides interpolation with user-specified 'chords.' These tools connected discrete channels between cross sections, preserving them in the interpolated cross sections.

The measured and simulated bed change volumes are plotted in Figure 2. Volume change results are normalized by longitudinal distance (Δm^3/linear m) in order to compare model results to measurements at different node spacings. Model results were also compared to the sediment concentrations measured 500 m downstream of the dam during the flush (Figure 3).

The model reproduced downstream deposition and erosion in the region 500 to 2000 m upstream of the dam very well. It under predicted scour in the 500 m immediately upstream of the dam. About half of the mass eroded from the foreset of the delta was eroded by post-incision channel widening, phase IV, in the Schumm *et al.,* (1984) channel evolution model. This is a limitation of the veneer method used in HEC-RAS, which only computed vertical bed change and cannot erode dry nodes once they channel incision strands them above the eroding channel.

HEC-RAS computed incision well, but underestimated erosion from lateral processes. Integrating the USDA-ARS Bank Erosion and Toe Scour Model (BSTEM), which includes lateral scour and bank failure processes with vertical bed change in HEC-RAS 5.0, may improve this result.

The concentration time series computed downstream of the dam tracked the measured concentrations well. The result in Figure 3 was a model validation, reported without additional parameterization beyond the calibration in Figure 2. The computed concentrations track the high bound of the measured concentrations. This is appropriate since the model reports total load, the measurements are suspended load, and substantial bed load (unmeasured load) is likely during high concentration events.

4.2 *Depositional calibration*

After simulating the flush, the same model was applied to the depositional period that followed. Approximately 350,000 m^3 of sediment deposited in the reservoir in the 5 months after the flush, replacing about half the sediment evacuated by the flush. These deposits formed a prograding delta in the channel the flush scoured through the reservoir sediment. The delta advanced roughly a kilometer into the reservoir during these five months. The calibrated sediment model should reproduce this delta formation.

The same parameters used for the flushing model (Yang, Copleand, and the same bed gradation) were adopted for the depositional model. Only two changes distinguished the flushing model from the depositional model. First, the October 2014 cross sections, representing the pre-flush conditions, were replaced with cross sections collected in early November, a few days after the flush. Second, the depositional model was calibrated by adjusting the upstream sediment boundary condition. The model was calibrated by adjusting the

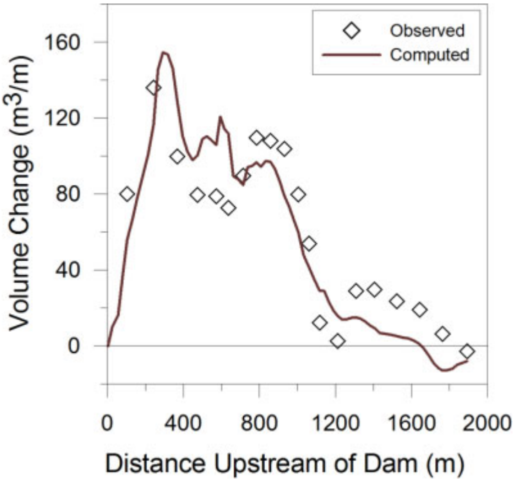

Figure 4. Flood debris found along the base of a cohesive lens in the reservoir sediment, corroborating Colby and Hembree's (1955) conclusion that high flows transport fine sediment.

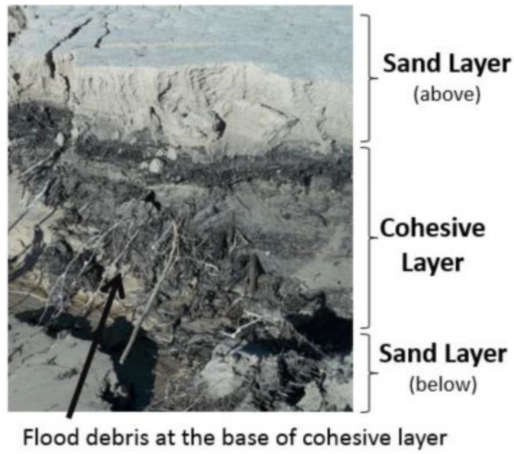

Figure 5. Post flush reservoir deposition calibration. The bed change volume in the reservoir, computed by HEC-RAS in the five months after the flush, is plotted with the observed bed volume change, from repeated cross sections.

coefficients and gradation of a sediment-flow rating curve. The calibrated sediment rating curve was:

$$Qs = 0.46\ Q^{1.2}$$

Additionally, the calibrated inflowing sediment fined as flow increased. Finer sediment loads at higher flows followed Colby and Hembree (1955) who measured uniform fine sand (median grain size between ~0.13 and 0.22 mm) in the Niobrara River at loads less than about 10,000 tonnes/day. However, at loads above 10,000 tonnes/day, Colby and Hembree (1955) collected mostly fine sediment (~.015 to 0.04 mm median grain size). Field observations also supported this non-linear, inverse relationship between flow and sediment size. Sediment cores and exposed banks from channels insized during the flush provided insight on reservoir sediment stratigraphy. Fine sediment layers interbedded with the sand that dominated the reservoir sediment. The bottom of these fine lenses was often lined with flood debris, (Figure 5) suggesting high flows deliver much finer loads.

The deposition calibration (sediment volume change) is included in Figure 6. The model reproduced the depositional distribution measured from the repeated cross section very well.

5 MODELING SUSTAINABLE SEDIMENT ALTERNATIVES THAT MITTIGATE DOWNSTREAM IMPACTS

Downstream impacts are one of the primary obstacles to sustainable sediment management alternatives like flushing and routing. Stakeholders often object to sediment releases from drawdown or pass through strategies because of downstream concerns about sediment concentration. Sediment releases are often limited by quantitative downstream concentration constraints (e.g. TMDLs).

After the Spencer Dam sediment model was calibrated for both the flushing scour and post-flush deposition, modelers experimented with alternate release schedules designed to automatically mitigate downstream concentrations, defining concentration controlled operational rules in HEC-RAS. HEC-RAS considered pre-defined concentration constraints to design two alternate relapse schedules:

1. An alternate flush (reservoir drawdown) that constrained gate operations, keeping downstream concentrations below a pre-defined limit.
2. A routing (sediment pass through) alternative that passed the high sediment concentrations associated with the largest flows through the reservoir, limiting downstream concentrations to those flowing into the reservoir (C_{out} C_{in}).

5.1 *Concentration controlled flushing: maintaining a downstream concentration threshold (e.g. TMDL)*

Reservoir *flushing* operations draw down reservoir pools to run of river conditions, scouring previously deposited sediment (Morris et al, 2008). Because they scour historical sediment deposits, flushing events release more sediment than the river supplies during the event. These elevated sediment releases can invoke regulatory standards, limiting release concentrations downstream. It is difficult to design a flush to meet downstream concentration limits *a priori.*

A downstream concentration trigger was added to the operational rules in HEC-RAS to simulate a downstream concentration constraint. The model

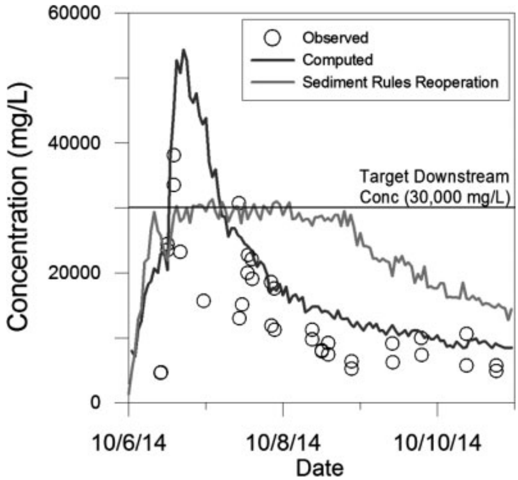

Figure 6. The downstream concentration calibration from Figure 4, plotted with an automated re-operation HEC-RAS run. The operational rules controlled the gates to limit the downstream concentration to a 30,000 mg/L target.

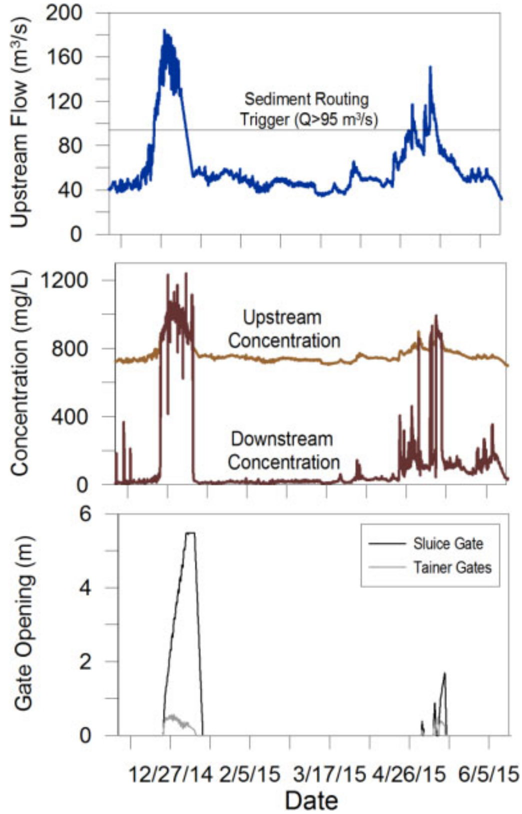

Figure 7. The Winter and Spring flows were modelled with operational rules that opened the gates to route sediment for flows greater than 95 m^3/s but limit concentration downstream of the dam to approximately the concentration entering the reservoir. The panels show the hydrograph (top), the upstream and downstream concentrations (middle), and the gate operations the model automatically computed (bottom).

automatically operated the gates, altering the flushing release schedule to maintain the downstream concentration control (30,000 mg/L). The re-regulated downstream concentration time series is plotted with the computed and measured results of the unconstrained flush in Figure 7.

5.2 *Concentration controlled routing: operating the reservoir to keep downstream concentration below inflow concentration*

Reservoir *routing*, is a alternative to reservoir flushing (Morris and Fan, 1998). Routing passes flows with the highest sediment concentrations, (e.g. flood flows or the rising limb hydrographs) through the reservoir, reducing sediment deposits in the reservoir, extending the reservoir life. In principle, routing reservoir sediment maintains the natural sediment regime of the pre-dam river. By only passing the naturally transported sediment through the reservoir, routing does not add anthropogenic surcharges to river concentrations.

However, it is difficult to operate a reservoir full of sediment to pass suspended load through the length of the pool without also entraining historical deposits, raising concentrations. Additionally, sediment, particularly sediment coarser than 0.063 mm, does not simply pass through a reach. Even in equilibrium, where the sediment leaving the reach is equal to the sediment entering the reach, the sediment that leaves is not the same sediment that enters. In an equilibrium condition there is constant exchange between transporting sediment and the bed. Therefore, operations that maintain the natural sediment regime, limiting sediment releases to the concentration entering the reservoir can be complex, including complicated feedbacks, and very difficult to design or even model. However, the same approach, where operational rules with concentration triggers automatically generate operations that maintain downstream concentrations constraints during a flush could compute operations for a routing event.

The Spencer dam model was re-run with routing rules. A flow trigger and a concentration control were added to the operational rules for the *depositional* model (November 2014 to May 2015). The reservoir held a constant pool (458.4 m) for most flows, sending all flow through the hydropower facility and depositing all sediment in the reservoir. However, when inflow hydrograph exceeded 95 m^3/s, (Figure 7, Top) the model switched to sediment routing operations, passing the sediment laden high flows though the sluice and tainer gates. The concentration control monitored the upstream and downstream concentrations and constrained the gate operations to limit

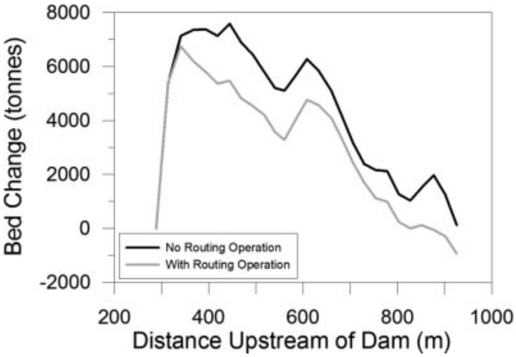

Figure 8. The deposition profile in the reservoir with and without the routing operation. Sediment routing at the moderate event decreased winter and spring deposition by 23%.

downstream concentrations to approximately the concentration entering the reservoir during the high flows (Figure 8, middle). Small concentration perturbations occasionally rise above the upstream concentration for one or two 30 second time steps, but these numerical artifacts would not be significant in an actual operation. The model automatically computed the reservoir gate operations to achieve this alternative (Figure 8, bottom).

If reservoir operations can limit downstream concentrations to the run-of-river concentrations entering the reservoir, they remove the effect of the structure for those flows, maintaining a more natural sediment regime, while extending the reservoir life. Timing a concentration controlled routing event with the spring peak flows decreased reservoir deposition 23% by mass (Figure 9).

6 CONCLUSION

A 1D sediment transport model simulated a reservoir flush and subsequent reservoir deposition at Spencer

Dam, replicating measured bed change and concentration reasonably well. This calibrated reservoir flushing model was then reoperated, using the concentration controlled operational rules in HEC- RAS 5.0. The model automatically generated flushing and routing operations that observed downstream concentration constraints. These operations can be very difficult to design. These results demonstrate the value of coupling a mechanistic 1D sediment transport model with concentration controlled reservoir operations when designing reservoir releases that pass sediment.

ACKNOWLEDGMENTS

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APPENDIX: HEC-RAS OPERATIONAL RULES CODE

This appendix includes the code used to define the operational rules in HEC-RAS 5.0 for the two simulations described in Section 5.

Concentration controlled flushing

```
! Define Variables to Monitor Flow and Concentration at Defined XSs
!
'DS_Conc' = Cross Sections:Sediment Concentration(Niobrara River,Reach 1,179818.5
'US_Conc' = Cross Sections:Sediment Concentration(Niobrara River,Reach 1,186329.9
'US_Flow' = Cross Sections:Flow(Niobrara River,Reach 1,186329.9
'Res_Stage' = Cross Sections:WS Elevation(Niobrara River,Reach 1,180298
!
! Route sediment for Q>3500
If ('US_Flow' > 3500) Then
    Gate.Closing Rate(2_Tainter) = 0.004
    Gate.Closing Rate(4_Sluice) = 0.005
    Gate.Opening Rate(1_Operation) = 0.002
    Structure.Stage (Fixed) = [not set]
    Gate.Opening(4_Sluice) = 0
    Gate.Opening(2_Tainter) = [not set]
    Gate.Flow (Desired)(4_Sluice) = [not set]
    Gate.Flow (Desired)(2_Tainter) = [not set]
    If ('DS_Conc' < 'US_Conc') Then
        !
        ! Open Gate
        Structure.Total Flow (Desired) = [not set]
        Gate.Opening(4_Sluice) = 'Res_Stage'-1481
        Gate.Opening(2_Tainter) = 3
    Else
        !
        ! Close Gate
        Gate.Opening(4_Sluice) = [not set]
        Gate.Opening(2_Tainter) = [not set]

          Structure.Total Flow (Desired) = 0
     End If
  Else
     !
     ! If flow is <3500 cfs re-fill
     Gate.Flow (Desired)(4_Sluice) = [not set]
     Gate.Opening(2_Tainter) = [not set]
     Gate.Opening(1_Operation) = [not set]
     Structure.Total Flow (Desired) = [not set]
     If ('Res_Stage' < 1503.9) Then
         Gate.Opening Rate(1_Operation) = 0.001
         Gate.Closing Rate(4_Sluice) = 0.003
         Gate.Closing Rate(2_Tainter) = 0.0004
         Gate.Flow (Desired)(1_Operation) = 10
         Gate.Opening(4_Sluice) = 0
         Gate.Opening(2_Tainter) = 0
         Gate.Flow (Desired)(4_Sluice) = [not set]
         Gate.Flow (Desired)(2_Tainter) = [not set]
     Else
         Gate.Opening(4_Sluice) = 0
         Gate.Opening(2_Tainter) = 0
         Gate.Opening(1_Operation) = [not set]
         Structure.Stage (Fixed) = 1504
         Gate.Flow (Desired)(4_Sluice) = [not set]
         Gate.Flow (Desired)(2_Tainter) = [not set]
         Gate.Flow (Desired)(1_Operation) = [not set]
     End If
  End If
```

Concentration controlled routing

```
! Define Variables to Monitor Flow and Concentration at Defined XSs
!
'DS_Conc' = Cross Sections:Sediment Concentration(Niobrara River,Reach 1,179818.5
'US_Conc' = Cross Sections:Sediment Concentration(Niobrara River,Reach 1,186329.9
'US_Flow' = Cross Sections:Flow(Niobrara River,Reach 1,186329.9
'Res_Stage' = Cross Sections:WS Elevation(Niobrara River,Reach 1,180298
!
! Route sediment for Q>3500
If ('US_Flow' > 3500) Then
    Gate.Closing Rate(2_Tainter) = 0.004
    Gate.Closing Rate(4_Sluice) = 0.005
    Gate.Opening Rate(1_Operation) = 0.002
    Structure.Stage (Fixed) = [not set]
    Gate.Opening(4_Sluice) = 0
    Gate.Opening(2_Tainter) = [not set]
    Gate.Flow (Desired)(4_Sluice) = [not set]
    Gate.Flow (Desired)(2_Tainter) = [not set]
    If ('DS_Conc' < 'US_Conc') Then
        !
        ! Open Gate
        Structure.Total Flow (Desired) = [not set]
        Gate.Opening(4_Sluice) = 'Res_Stage'-1481
        Gate.Opening(2_Tainter) = 3
    Else
        !
        ! Close Gate
        Gate.Opening(4_Sluice) = [not set]
        Gate.Opening(2_Tainter) = [not set]

          Structure.Total Flow (Desired) = 0
     End If
  Else
     !
     ! If flow is <3500 cfs re-fill
     Gate.Flow (Desired)(4_Sluice) = [not set]
     Gate.Opening(2_Tainter) = [not set]
     Gate.Opening(1_Operation) = [not set]
     Structure.Total Flow (Desired) = [not set]
     If ('Res_Stage' < 1503.9) Then
         Gate.Opening Rate(1_Operation) = 0.001
         Gate.Closing Rate(4_Sluice) = 0.003
         Gate.Closing Rate(2_Tainter) = 0.0004
         Gate.Flow (Desired)(1_Operation) = 10
         Gate.Opening(4_Sluice) = 0
         Gate.Opening(2_Tainter) = 0
         Gate.Flow (Desired)(4_Sluice) = [not set]
         Gate.Flow (Desired)(2_Tainter) = [not set]
     Else
         Gate.Opening(4_Sluice) = 0
         Gate.Opening(2_Tainter) = 0
         Gate.Opening(1_Operation) = [not set]
         Structure.Stage (Fixed) = 1504
         Gate.Flow (Desired)(4_Sluice) = [not set]
         Gate.Flow (Desired)(2_Tainter) = [not set]
         Gate.Flow (Desired)(1_Operation) = [not set]
     End If
  End If
```